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Fejer **EDITION**

**Properties and Selection:
Irons, Steels, and
High-Performance Alloys**



Wrought Stainless Steels

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STAINLESS STEELS are iron-base alloys containing at least 10.5% Cr. Few stainless steels contain more than 30% Cr or less than 50% Fe. They achieve their stainless characteristics through the formation of an invisible and adherent chromium-rich oxide surface film. This oxide forms and heals itself in the presence of oxygen. Other elements added to improve particular characteristics include nickel, molybdenum, copper, titanium, aluminum, silicon, niobium, nitrogen, sulfur, and selenium. Carbon is normally present in amounts ranging from less than 0.03% to over 1.0% in certain martensitic grades.

The selection of stainless steels may be based on corrosion resistance, fabrication characteristics, availability, mechanical properties in specific temperature ranges and product cost. However, corrosion resistance and mechanical properties are usually the most important factors in selecting a grade for a given application.

Original discoveries and developments in stainless steel technology began in England and Germany about 1910. The commercial production and use of stainless steels in the United States began in the 1920s, with Allegheny, Armco, Carpenter, Crucible, Firth-Sterling, Jessop, Ludlum, Republic, Rustless, and U.S. Steel being among the early producers.

Only modest tonnages of stainless steel were produced in the United States in the mid-1920s, but annual production has risen steadily since that time. Even so, tonnage has never exceeded about 1.5% of total production for the steel industry. Table 1 shows shipments of stainless steel over a recent 10-year period. Production tonnages are listed only for U.S. domestic production. France, Italy, Japan, Sweden, the United Kingdom, and West Germany produce substantial tonnages of steel, and data on production in these countries are also available. However, other free-world countries do not make their figures public, and production statistics are not available from the U.S.S.R. or other Communist nations, which makes it impossible to estimate accurately the total world production of stainless steel.

The development of precipitation-hardenable stainless steels was spearheaded by the successful production of Stainless W by U.S. Steel in 1945. Since then, Armco, Allegheny-Ludlum, and Carpenter Technology have developed a series of precipitation-hardenable alloys.

The problem of obtaining raw materials has been a real one, particularly in regard to nickel during the 1950s when civil wars raged in Africa and Asia, prime sources of nickel, and Cold War politics played a role because Eastern-bloc nations were also prime sources of the element. This led to the development of a series of alloys (AISI 200 type) in which manganese and nitrogen are partially substituted for nickel. These stainless steels are still produced today.

New refining techniques were adopted in the early 1970s that revolutionized stainless steel melting. Most important was the argon-oxygen-decarburization (AOD) process. The AOD and related processes, with different gas injections or partial pressure systems, permitted the ready removal of carbon without substantial loss of chromium to the slag. Furthermore, low carbon contents were readily achieved in 18% Cr alloys when using high-carbon ferrochromium in furnace charges in place of the much more expensive low-carbon ferrochromium. Major alloying elements could also be controlled more precisely, nitrogen became an easily controlled intentional alloying element, and sulfur could be reduced to exceptionally low levels when desired. Oxygen could also be reduced to low levels and, when coupled with low sulfur, resulted in marked improvements in steel cleanliness.

During the same period, continuous casting grew in popularity throughout the steel industry, particularly in the stainless steel segment. The incentive for continuous casting was primarily economic. Piping can be confined to the last segment to be cast such that yield improvements of approximately 10% are commonly achieved. Improvements in homogeneity are also attained.

Over the years, stainless steels have become firmly established as materials for

cooking utensils, fasteners, cutlery, flatware, decorative architectural hardware, and equipment for use in chemical plants, dairy and food-processing plants, health and sanitation applications, petroleum and petrochemical plants, textile plants, and the pharmaceutical and transportation industries. Some of these applications involve exposure to either elevated or cryogenic temperatures; austenitic stainless steels are well suited to either type of service. Properties of stainless steels at elevated temperatures are discussed in the section "Elevated-Temperature Properties" of this article and more detailed information is available in the article "Elevated-Temperature Properties of Stainless Steels" in this Volume. Properties at cryogenic temperatures are discussed in the section "Subzero-Temperature Properties" of this article.

Modifications in composition are sometimes made to facilitate production. For instance, basic compositions are altered to make it easier to produce stainless steel tubing and castings. Similar modifications are made for the manufacture of stainless steel welding electrodes; here, combinations of electrode coating and wire composition are used to produce desired compositions in deposited weld metal.

Classification of Stainless Steels

Stainless steels are commonly divided into five groups: martensitic stainless steels, ferritic stainless steels, austenitic stainless steels, duplex (ferritic-austenitic) stainless steels, and precipitation-hardening stainless steels.

Martensitic stainless steels are essentially alloys of chromium and carbon that possess a distorted body-centered cubic (bcc) crystal structure (martensitic) in the hardened condition. They are ferromagnetic, hardenable by heat treatments, and are generally resistant to corrosion only to relatively mild environments. Chromium content is generally in the range of 10.5 to 18%, and carbon content may exceed 1.2%. The chromium and carbon contents are balanced to ensure a martensitic structure after hardening. Ex-

Table 1 Total U.S. shipments of stainless steel over the 10-year period from 1979 to 1988

Year	Shipments	
	kt	1000 tons
1979	1234	1361
1980(a)	1022	1127
1981(a)	1055	1163
1982(a)	811	894
1983(a)	1032	1137
1984(a)	1132	1248
1985(a)	1135	1251
1986(a)	1077	1187
1987(a)	1287	1418
1988(b)	1439	1586

(a) Ref 1. (b) Ref 2

cess carbides may be present to increase wear resistance or to maintain cutting edges, as in the case of knife blades. Elements such as niobium, silicon, tungsten, and vanadium may be added to modify the tempering response after hardening. Small amounts of nickel may be added to improve corrosion resistance in some media and to improve toughness. Sulfur or selenium is added to some grades to improve machinability.

Ferritic stainless steels are essentially chromium containing alloys with bcc crystal structures. Chromium content is usually in the range of 10.5 to 30%. Some grades may contain molybdenum, silicon, aluminum, titanium, and niobium to confer particular characteristics. Sulfur or selenium may be added, as in the case of the austenitic grades, to improve machinability. The ferritic alloys are ferromagnetic. They can have good ductility and formability, but high-temperature strengths are relatively poor compared to the austenitic grades. Toughness may be somewhat limited at low temperatures and in heavy sections.

Austenitic stainless steels have a face-centered cubic (fcc) structure. This structure is attained through the liberal use of austenitizing elements such as nickel, manganese, and nitrogen. These steels are essentially nonmagnetic in the annealed condition and can be hardened only by cold working. They usually possess excellent cryogenic properties and good high-temperature strength. Chromium content generally varies from 16 to 26%; nickel, up to about 35%; and manganese, up to 15%. The 2xx series steels contain nitrogen, 4 to 15.5% Mn, and up to 7% Ni. The 3xx types contain larger amounts of nickel and up to 2% Mn. Molybdenum, copper, silicon, aluminum, titanium, and niobium may be added to confer certain characteristics such as halide pitting resistance or oxidation resistance. Sulfur or selenium may be added to certain grades to improve machinability.

Duplex stainless steels have a mixed structure of bcc ferrite and fcc austenite. The exact amount of each phase is a function of composition and heat treatment (see the

article "Cast Stainless Steels" in this Volume). Most alloys are designed to contain about equal amounts of each phase in the annealed condition. The principal alloying elements are chromium and nickel, but nitrogen, molybdenum, copper, silicon, and tungsten may be added to control structural balance and to impart certain corrosion-resistance characteristics.

The corrosion resistance of duplex stainless steels is like that of austenitic stainless steels with similar alloying contents. However, duplex stainless steels possess higher tensile and yield strengths and improved resistance to stress-corrosion cracking than their austenitic counterparts. The toughness of duplex stainless steels is between that of austenitic and ferritic stainless steels.

Precipitation-hardening stainless steels are chromium-nickel alloys containing precipitation-hardening elements such as copper, aluminum, or titanium. Precipitation-hardening stainless steels may be either austenitic or martensitic in the annealed condition. Those that are austenitic in the annealed condition are frequently transformable to martensite through conditioning heat treatments, sometimes with a subzero treatment. In most cases, these stainless steels attain high strength by precipitation hardening of the martensitic structure.

Standard Types. A list of standard types of stainless steels, similar to those originally published by the American Iron and Steel Institute (AISI), appears in Table 2. The criteria used to decide which types of stainless steel are standard types have been rather loosely defined but include tonnage produced during a specific period, availability (number of producers), and compositional limits. Specification-writing organizations such as ASTM and SAE include these standard types in their specifications. In referring to specific compositions, the term type is preferred over the term grade. Some specifications establish a series of grades within a given type, which makes it possible to specify properties more precisely for a given nominal composition.

In each of the three original groups of stainless steels—*austenitic*, *ferritic*, and *martensitic*—there is one composition that represents the basic, general-purpose alloy. All other compositions derive from this basic alloy, with specific variations in composition being made to impart very specific properties. The so-called family relationships for these three groups are summarized in Fig. 1 to 3. Type 329 is a duplex stainless steel (about 80% ferrite, 20% austenite as annealed) and is listed separately in Table 2.

Nonstandard Types. In addition to the standard types, many proprietary stainless steels are used for specific applications. Compositions of the more popular, nonstandard stainless steels are given in Table 3; some of the nonstandard grades are identified by AISI type numbers.

A cooperative study of ASTM and SAE resulted in the Unified Numbering System (UNS) for designation and identification of metals and alloys in commercial use in the United States. In UNS listings, stainless steels are identified by the letter S, followed by five digits. A few stainless alloys are classified as nickel alloys in the UNS system (identification letter N) because of their high nickel and low iron (less than 50%) contents.

Use of UNS numbers and AISI standard-type numbers ensures that a consumer can obtain suitable material time after time even from different producers or suppliers. Nevertheless, some variation in fabrication and service characteristics can be expected, even with material obtained from a single producer.

Factors in Selection

The first and most important step toward successful use of a stainless steel is selection of a type that is appropriate for the application. There are a large number of standard types that differ from one another in composition, corrosion resistance, physical properties, and mechanical properties; selection of the optimum type for a specific application is the key to satisfactory performance at minimum total cost.

The characteristics and properties of individual types discussed in this article and elsewhere in this Volume provide some of the information useful in steel selection. For a more detailed discussion, the reader is referred to *Design Guidelines for the Selection and Use of Stainless Steel*, published by the Committee of Stainless Steel Producers and available through AISI.

A checklist of characteristics to be considered in selecting the proper type of stainless steel for a specific application includes:

- Corrosion resistance
- Resistance to oxidation and sulfidation
- Strength and ductility at ambient and service temperatures
- Suitability for intended fabrication techniques
- Suitability for intended cleaning procedures
- Stability of properties in service
- Toughness
- Resistance to abrasion and erosion
- Resistance to galling and seizing
- Surface finish and/or reflectivity
- Magnetic properties
- Thermal conductivity
- Electrical resistivity
- Sharpness (retention of cutting edge)
- Rigidity

Corrosion resistance is frequently the most important characteristic of a stainless steel, but often is also the most difficult to assess for a specific application. General corrosion resistance to pure chemical solu-